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PARTICLE BED REACTOR MODELING

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View Graph 3 - Acknowledgements

The systems analysis shown in this work was supported by The Space Nuclear Thermal Propulsion Program. The pioneering work on PBR applications to nuclear thermal propulsion systems by Brookhaven National Laboratory is also acknowledged.

PARTICLE BED REACTOR MODELING

- PRESENT THERMAL-HYDRAULIC SYSTEM MODELING TOOLS B&W USES FOR NTP SYSTEMS
- FOCUS ON PARTICLE BED REACTOR TECHNOLOGY AND THERMAL HYDRAULIC METHODS.

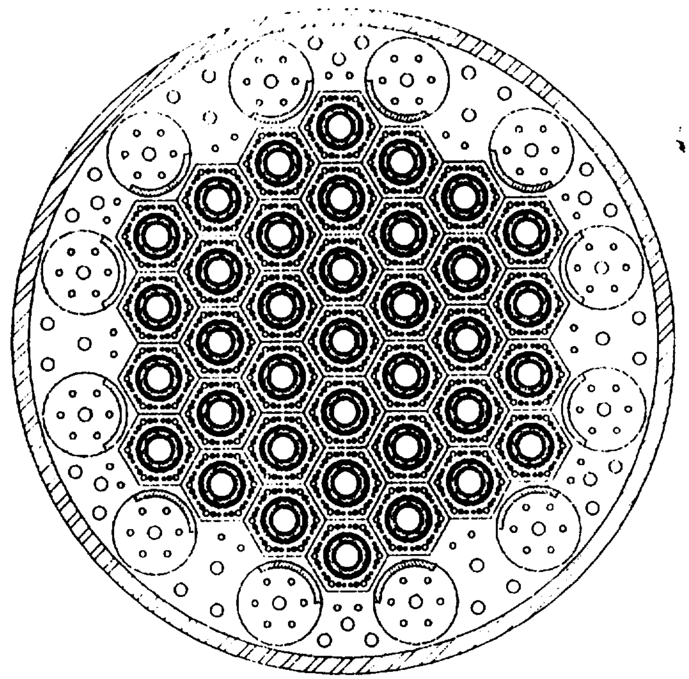
View Graph 4 - Particle Bed Reactor Modeling

The purpose of this discussion is to present to you the thermal-hydraulic system modeling tools B&W uses for nuclear thermal propulsion systems. It will focus on the particle bed reactor technology and the thermal-hydraulic methods used to analyze it. These have received special attention by NASA and others who feel that thermal-hydraulic modeling is a critical issue for nuclear thermal propulsion systems.

The PBR design has received particular scrutiny due to some misconceptions about how flow control is achieved with this technology. I plan to clear up these misunderstandings today.

There will be no discussion of reactor kinetics, reactor physics, or mechanical modeling which are nonetheless important. The presentation will cover some of the challenges of PBR modeling, the Computer codes and physical correllations used, and conclude with some results of analyses and a general philosophy of system modeling.

PBR CORE CROSS SECTION

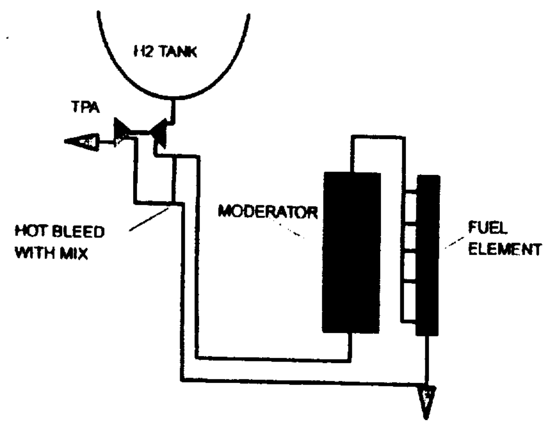


View Graph 5 - Radial Cross Section of Particle Bed Reactor

This view graph shows a radial cross section view of the reactor system we will be discussing today. This system is a generic particle bed reactor system made up of 37 fuel elements as shown by the red circles. The blue area surrounding the fuel elements are hexagonal moderator blocks. Some of the holes shown in the blocks are for propellant flow through the moderator.

This core is surrounded by a reflector and twelve control drums which are in turn surrounded by a pressure vessel. Details of particle bed reactor systems were presented in several papers at this workshop and won't be covered here.

PBR BLEED CYCLE



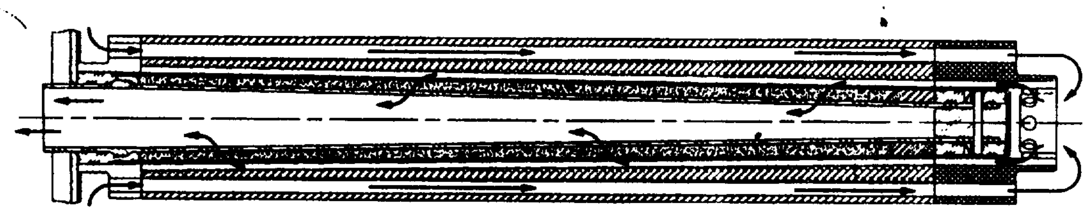
View Graph 6 - PBR Bleed Cycle

Several different flow cycles have been proposed for the PBR rocket system. I will not discuss those here except to describe the flow in the reactor system itself for a hot bleed cycle. In the hot bleed cycle shown here, the propellent is routed through cooling channels in the moderator, reflector and nozzle walls. The propellant may be split between any of the three components, or be separated by plenums and have a single pass cooling loop. Depending on design requirements, flow split and single pass concepts can be used for any combination of the moderator, reflector or nozzle wall flow paths.

The propellant exits the moderator and is collected in a plenum above the core. It is then sent through the fuel element and exits the engine via the nozzle. Target outlet temperatures are nominally very high to maintain high ISP. Mach number is about 0.25 at the outlet.

For purposes of reactor modeling there are three areas which are usually discussed separately since they require different types of computer codes and basic data for evaluation. These include the entire particle bed reactor rocket system, including turbo-pump assemblies. This system modeling will not be discussed here today. The other two areas are fluid flow in the entrance and exit plenums of the reactor system and finally modeling of fluid flow through the particle bed fuel element.

FUEL AND MODERATOR FLOW PATHS



View Graph 7 - Fuel Element Flow paths

This is a view of a particle bed fuel element with flow paths shown by arrows. The red hatched (outer) area is the moderator section; the orange area is the fuel bed and the green areas the innner (hot) and outer (cold) frits that hold the fuel particles.

A typical path has gas entering at the moderator to cool it, then to a plenum at the entrance side of the fuel element, or directly into the fuel element. Orificing of the element can be done at either the moderator entrance or the fuel element entrance.

The gas enters the cold frit which is at the outer annulus of the fuel element, then passes through the fuel bed, and hot frit where it turns and flows out the outlet channel.

Target outlet temperatures are high to maintain high specific impluse. Mach number is approximately 0.25 at the outlet.

PBR MODELING REQUIREMENTS

- ■1. FLUID FLOW THROUGH A PARTICLE BED
- ■2. COMPRESSIBLE AND INCOMPRESSIBLE FLOW
- ■3. SINGLE and TWO-PHASE FLOW
- ■4. COUPLES FLUID FLOW and SOLID HEAT TRANSFER

View Graph 8 - PBR Modeling Requirements

The dynamics of gas flow in this system is dominated by fluid flow characteristics through a packed particle bed. This has been extensively studied along with the application to gas cooled reactors both in this country and Europe.

Since exit Mach number is approximately 0.25, the flow can be treated as incompressible. However, because of the extremely large changes in density in going from the relatively cold inlet temperature to extremely high exit temperatures, thermally expandable flow techniques (fluid density independent of pressure changes) will be required. This can be modeled with the equations used for compressible flow or with a sepatate treatment using equations for thermally expandable flow.

Under normal steady state operation all flow is expected to be single phase, however there are potential accident transients and system cycles where two phase flow would have to be considered.

Computer codes and methods modeling this system will need separate fuel particle and fluid flow modeling to cover the complex thermal-hydraulic dynamics encountered in the fuel bed.

PBR MODELING REQUIREMENTS, Cont.

- RANGE OF SINGLE TO MULTI-DIMENSIONAL MODELING
- TRANSIENT AND STEADY-STATE ANALYSIS

View Graph 9 - PBR Modeling Requirements (Continued)

The computer codes used to analyze the fuel element will need multi-dimensional capabilities. The systems level analysis will use primarily one-dimensional techniques. Both transient and steady state analysis will be required to cover the wide range of operating and accident modes.

CHARACTERISTICS OF PBR and NTP MODELING

- 1. FUEL ELEMENT FLOW-TO-POWER MATCH
- 2. REACTOR FLOW-TO-POWER MATCH
- 3. BED TO COLD FRIT HEATING EFFECTS

View Graph 10 - Characteristics Of PBR and NTP Modeling

The most obvious characteristic of the PBR is flow-to-power matching in the fuel element which must occur to account for axial power distribution and dynamic head in the fuel element exit channel. Other effects like heat conduction from the bed to the cold frit and overall reactor flow-to-power matching to handle radial power distributions and orificing to elements must also be considered.

CHALLENGES FOR PBR and NTP MODELING

- 1. START UP TRANSIENTS
- 2. DECAY HEAT
- 3. THROTTLING CONDITIONS
- 4. ACCIDENT TRANSIENTS
- 5. PRE-TEST PREDICTIONS
- 6. COMPONENT HEATING

View Graph 11 - Challenges for PBR and NTP Modeling

This view graph lists a number of applications of modeling required for a PBR reactor. These also include use of modeling for designing tests and performing post-test evaluations. Examples of system analyses for Decay Heat cooling and Start Up Transients will be presented later.

THERMAL HYDRAULIC COMPUTER CODES

- **1. OTV ENGINE - B&W**
  - **PARTICLE BED FUEL ELEMENT DESIGN SPECIFIC**
- **2. TEMPEST - BATTELLE NORTHWEST**
  - **GENERAL 3-D CFD ANALYSIS**
- **3. SAFSIM - SANDIA**
  - **NETWORK SYSTEMS ANALYSIS CODE**
- **4. SINDA/SINFLO-NASA**
  - **DETAIL THERMAL ANALYZER**

View Graphs 12-21 - Thermal Hydraulic Computer Codes, Code Capabilities and Limitations

The next ten view graphs show the major thermal-hydraulic codes which have been used by B&W for analysis of NTP systems, along with some of their capabilities and limitations. Time doesn't allow a full discussion of these view graphs and the graphs are self-explanatory. Since most of the codes are available in the public domain their names are recognizable to you and won't be discussed. Some of these codes were developed by B&W and are not quite as well known. The primary code in this class was one called OTV Engine. This computer code is used extensively by B&W to provide the nominal fuel element design conditions and specifically to calculate cold frit masking factors that will meter the flow through the cold frit. This code is particularly useful in that it calculates pressure drops due to resistance of the material in the cold frit, and dynamic head effects from gas exiting in the hot channel to provide masking factors which will ensure boundary conditions of constant exit temperature in the exit channel.

You will notice that a wide range of codes are listed here since typically a single code or code system will not provide the combination of capabilities and features desirable for a wide variety of applications. The limitations listed for the major computer codes are a good indication of why a large number of codes are used. In general the one-dimensional network systems analysis codes like SAFSIM will be used for pipe flow and flow splits. The multi-dimensional codes like TEMPEST are used for fuel element analysis.

The SAFSIM Computer Code has been recently obtained from Sandia National Laboratory and has not had significant use by B&W to date, although we are currently in a program to evaluate this code because of its many promising features. This code will be covered by a separate presentation later today. Finally it should be noted that all the codes listed here are single phase. Two-phase capability will be required to analyze off nominal transient and/or accident conditions.

CAPABILITIES FOR PBR/REACTOR APPLICATION

- OTV-ENGINE
  - PROVIDES "NOMINAL" FUEL ELEMENT DESIGN CONDITION
    - SPATIAL FUEL TEMPERATURE
  - PROVIDES "OFF-NOMINAL" DESIGN CONDITIONS

THERMAL/HYDRAULIC CODES, cont.

- 5. ANSYS - SWANSON, INC.
  - DETAIL THERMAL CODE FOR COMPONENT AND LOOP ANALYSIS
- 6. NEST - B&W
  - TRANSIENT ANALYSIS OF COUPLED NEUTRONICS, THERMAL-HYDRAULICS
- 7. ATHENA - INEL
  - 1-D TRANSIENT OR STEADY STATE SIMULATION OF SPACE REACTORS

CAPABILITIES, cont.

- TEMPEST
  - MULTI DIMENSIONAL CFD ANALYSIS
  - ALLOWS ANALYSIS OF ACTUAL DESIGN
  - ADDRESSES COMPLEX THERMAL/FLOW
- SAFSIM
  - REACTOR AND ENGINE SYSTEM
- SINDA
  - GENERALIZED CONDUCTION AND 1-D CIRCUIT FLOW SPLIT MODELING CAPABILITY

CAPABILITIES, Cont.

- ANSYS
  - PERFORMS GENERALIZED DETAIL HEAT TRANSFER ANALYSIS
  - PROVIDES GENERAL COUPLED FLOW/CONDUCTION HEAT TRANSFER FOR SPECIFIED (KNOWN) FLOW REGIONS
- NEST
  - EVALUATION OF SYSTEM CONTROL

LIMITATIONS

- **OTV-E**
  - STEADY STATE
  - NO REACTOR PHYSICS
  - NO CONDUCTION (gas or solid)
  - NO GENERAL FEATURE CAPABILITY
  - CHANNEL APPROACH TO FLOW (1-D)

LIMITATIONS, cont.

- **TEMPEST**
  - NO REACTOR PHYSICS
  - LIMITED TO ORTHOGONAL CURVELINEAR GEOMETRICS AT PRESENT
  - TIME STEP LIMITED TO "MATERIAL-COURANT
- **SAFSIM**
  - TIME STEP LIMITED TO "MATERIAL-COURANT"
  - PSEUDO MULTIDIMENSIONAL (1-D FLOW, NETWORK HEAT TRANSFER)

LIMITATIONS, cont.

- NEST
  - POINT KINETICS
  - QUASI-STEADY FLUID FLOW
- SINDA
  - MODEL DEFINITION IS TEDIOUS
  - FLOW IS INCOMPRESSIBLE
  - NO SPECIFIC PROVISION FOR FLUID FLOW THROUGH PARTICLE BED
  - STEADY STATE

LIMITATIONS, cont.

- ANSYS
  - STEADY STATE FLOW
  - INCOMPRESSIBLE FLOW ONLY
  - LACKS SPECIALIZED CORRELATION CAPABILITY (FRICTION, FILM COEFFICIENT, etc.)
  - PSEUDO MULTI-DIMENSIONAL (1-D FLOW, 3-D HEAT TRANSFER)
- ALL CODES LISTED ARE SINGLE PHASE - WILL NEED TWO PHASE CAPABILITY

PHYSICAL CORRELATIONS

- SPECIFIC CORRELATIONS FOR PARTICLE BED
  - FILM COEFFICIENTS - ACHENBACH
  - FRICTION COEFFICIENT - ERGUN
- FUEL ELEMENT COMPONENTS (COLD & HOT FRITS)
  - MODIFY GENERALIZED CORRELATIONA FOR SPECIFIC APPLICATION BASED ON EXPERIMENTAL DATA

View Graph 22 - Physical Correlations

The next two view graphs provide some information on the second major component of systems modeling - the validity and determination of the physical parameters and correlations used for modeling of the system. These view graphs show well known correlations that have been used in particle bed modeling. They also identify the need for experimental verification of this data. B&W has performed many of the experiments required to verify this data.

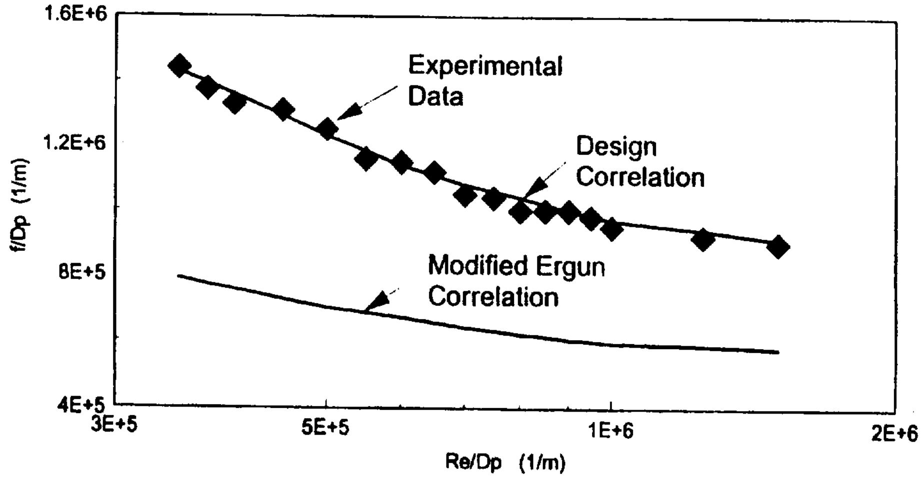
MODIFIED CORRELATIONS

- EXAMPLES
  - MODIFY ERGUN CORRELATION FOR COLD FRIT
  - FRICTION FACTORS FOR BLOWING AND SUCTION FLOW
  - PARTICLE BED CONDUCTIVITY - ZEHNER AND BAUER

View Graph 23 - Modified Correlations

Some examples of correlations that have been modified are shown here. They include friction coefficients for cold frits, friction factors for blowing and suction flow in the entrance and exit annulus of the fuel element and particle bed conductivity.

Comparison of Predicted Friction Factor and Experimental Data



View Graph 24 - Comparison of Predicted Friction Factor And Experimental Data

This view shows a comparison of a predicted friction factor correlation of a outer (cold) frit as compared to the design correlation determined from experimental data taken at B&W's Alliance Research Center. In this case, air was flowed through typical manufactured frits and pressure drop measurements performed. This plot is a measure of the normalized friction factor as a function of Reynolds number. As you can see the design correlation, which has an accuracy of plus or minus 10%, is approximately 30 to 40% higher than the theoretical friction factor and shows a steeper increase with lower Reynolds number.

In addition to tests of cold frit, B&W has used experimental data for friction factors covering blowing and suction flow in the fuel element annulus and have plans for performing tests on particle bed conductivity. As shown on the previous view graph, B&W currently uses the correlation of Zehner and Bauer for particle bed conductivity. This correlation was not developed for PBR applications and therefore will be experimentally verified.

FRIT PRESSURE DROP TESTING WITH H_2, AIR, and N_2

TEST CONDITIONS

P 3.2 MPa

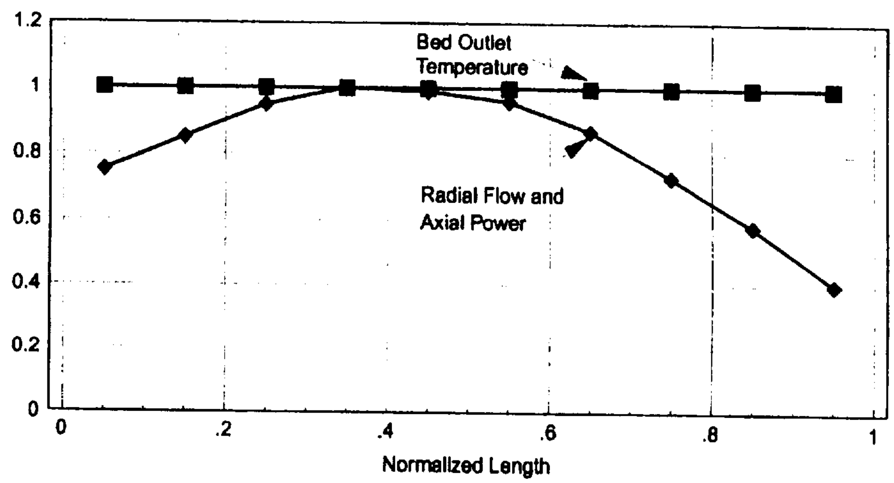
T 294 K

Gas	Re/Dp (10 1/m)	Kexp (10)	Kcalc (10)	(Kexp-Kcalc)/Kcalc (%)
Air	5.08	5.51	5.43	+1.5
Air	5.02	5.36	5.48	- 2.2
H_2	5.38	5.25	5.19	+1.2
H_2	5.38	5.27	5.19	+1.5
N_2	5.04	5.39	5.47	-1.5

View Graph 25 - Frit Pressure Drop Testing

This table shows some results of pressure drop measurements on a outer (cold) frit using hydrogen, air and nitrogen. In this case the data and calculations compare well. It also shows that you can use different gas at the same Reynolds number and get meaningful results.

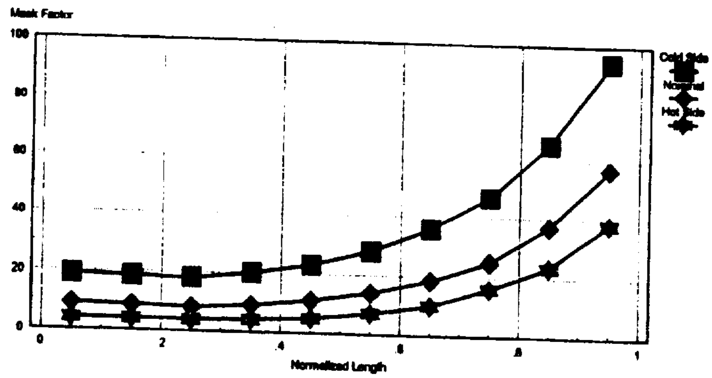
COLD FRIT FLOW-TO-POWER MATCHING



View Graph 26 - Cold Frit Flow-To-Power Matching

Before we get into decay heat cooling, we should show how we control flow to match power at normal operation. The view graph demonstrates the fact that the radial flow into the outer (cold) frit must match the axial power distribution in order to obtain a constant outlet temperature. This metered-flow design is basic to the PBR concept.

COLD FRIT MASK FACTOR
With Azimuthal Power Variations



View Graph 27 - Cold Frit Mask Factor - Azimuthal Variation

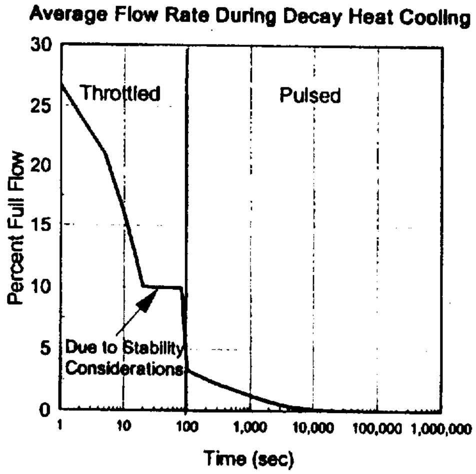
In order to match flow to power in all locations on the outer (cold) frit, friction or masking factors are used to design the frit such that the flow matches the power. In effect assuring that less resistance to flow occurs at the hotter spots.

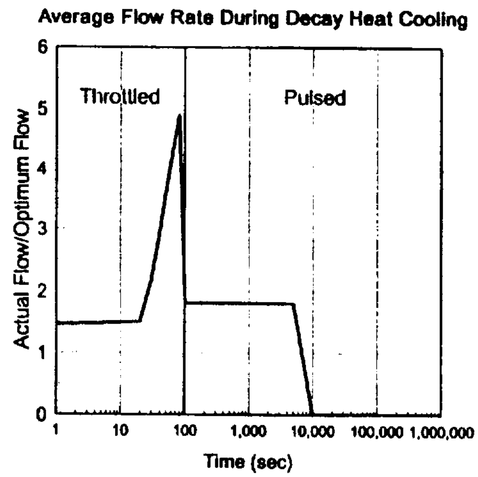
This view graph shows typical masking factor variation along the axial direction of the element. The three curves are for the hot, cold, and nominal (average) power sides of the frit. These differences account for the azimuthal variation around the element produced by the radial change in power in the reactor.

The next segment covers decay heat cooling. Since power, or heat source, distributions change during idlying (decay heat) operation, total flow through the element must account for the fact that the cold frits were masked to match the power at full power operation. This is usually done by supplying excess flow to the element.

The next series of view graphs will show some results of analysis performed for decay heat (idling condition) and start up conditions in a particle bed reactor.

Decay Heat Flow Rate



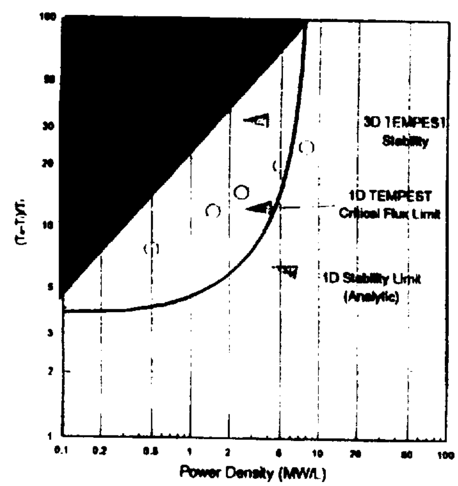


View Graph 28 - Decay Heat Flow Rate

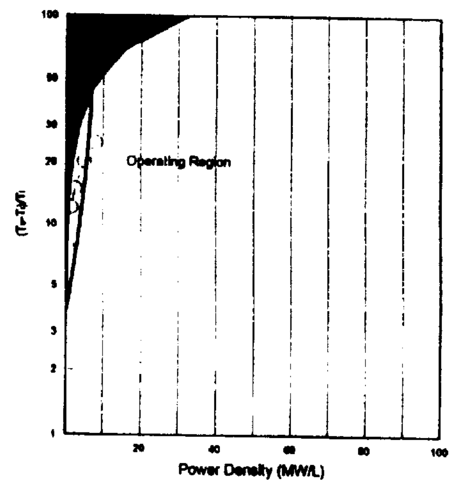
This view graph shows a typical evaluation of the propellant flow rate required after shut-down to cool a particle bed reactor under decay heating caused by the gamma and beta radiation being emitted by nuclear fuel after shut-down. The scenario used for decay heat cooling is to maintain a throttled overflow of propellant for approximately the first 100 seconds after shut-down to insure a cool geometry. The flow is gradually decreased to match the declining power output of the core until the 10% flow plateau is reached. This flow is maintained constant for a while due to stability considerations which I will discuss later. The system then converts to pulse cooling similar to that planned for the NERVA engine. Pulse cooling continues through approximately 10,000 seconds or until the system gets to approximately one to two percent of full power. At this point a long-term closed cycle cooling system would be used to keep the reactor cooled through some type of closed loop system. This system would radiate the small excess heat to space. The view graph on the right is a plot of the actual predicted flow to the optimum flow needed for this process. In this case optimum flow would be that flow needed to exactly match flow to system heat rate. As you can see there is a spike where the actual flow exceeds the optimum flow by approximately five times for a short period of time to accommodate instability limits.

It should be noted that the numbers shown here were obtained with analysis of a single fuel element. They do not account for flow splits in the total system. Also no mechanical analysis were performed to determine the effects of thermal cycling during pulsed cooling.

Stability Regimes



LOG SCALE



LINEAR SCALE

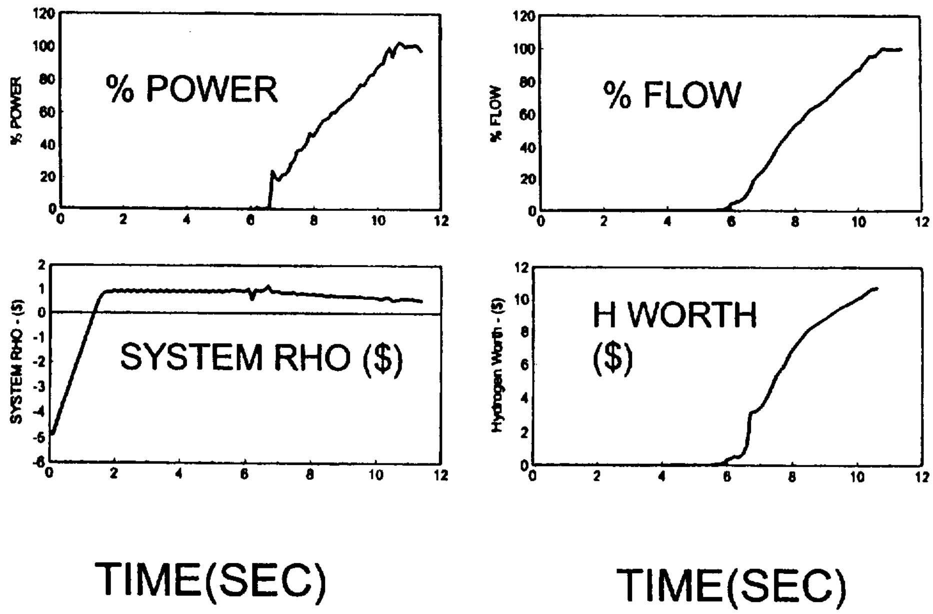
View Graph 29 - Stability Regimes

This view graph shows two presentations of the same data. The one on the left using a log scale for the "x" axis and the one on the right using a linear scale for the "x" axis. The "y" axis is a plot of a instability index developed by Bussard based on NERVA data and applied by Maise of Brookhaven National Laboratory to particle bed systems. This index is the difference between the inlet and the outlet temperature divided by the inlet temperature and here it is shown as a function of power density. If you focus your attention to the view graph on the right, the open area is that region where flow instabilities would not occur. The shaded region is where there are potential flow instabilities. In the case discussed here, the shaded area is only approached during decay heat cooling and is not a factor in the operating regions.

The view graph on the left shows an example of how the unstable region shrinks as one performs more detailed analysis of flow instabilities. The curve shown at the right labeled 1-D stability limit is the analytical result obtained by Bussard. The open circles represent a shift of the one-dimensional stability regime when analyzed with the computational fluid dynamics computer code TEMPEST. The darkly shaded areas show even further movement when a particle bed system is analyzed with three dimensional codes. In this case the area is shown shaded because no sharp boundary exists. Instead we are predicting a gradually increasing probability of flow maldistribution. The actual region of instability would have to be verified by experiment because of these uncertainties. These curves show the advantages of using multi-dimensional analysis on these complex geometries.

We need to note that this is not only a PBR problem - all gas reactors will need to accommodate instability limits at low flow/high delta T conditions.

STARTUP TRANSIENT SIMULATION



View Graph 30 - Start-up Transient Simulation

This view graph gives a representative example of an analysis performed for the start-up of a particle bed reactor. This analysis was done with B&W's NEST computer code system. It was performed to evaluate the unusually high reactivity insertion from flowing cold hydrogen during start-up of the system. In particular it was being used to evaluate the effectiveness of the control mechanisms to mitigate the large insertion of positive reactivity into the system during start-up. These slides show the percent power, percent hydrogen flow, hydrogen worth, and reactivity change of the system versus time over a period of approximately twelve seconds. This analysis shows the system can achieve and maintain design power.

The start up scenario used here is "dry". The reactor is taken critical before hydrogen flow is initiated. As hydrogen starts to flow one set of control elements is moved to overcome the positive reactivity insertion caused by hydrogen flow. Another set of control elements, with different characteristics from the first, is used to control power. The control algorithm controls to a demand startup period while constrained by maximum power versus flow requirements which are shown in this viewgraph.

PHILOSOPHY OF SYSTEMS MODELING

- THE PROOF OF THE PUDDING IS IN THE TESTING
- LEARN FROM EXPERIENCE
  - SKYLAB and HUBBLE
- SYSTEMS MODELING IS A GUIDE FOR PERFORMANCE AND TESTING. IT IS NOT THE FINAL WORD

View Graph 31 - Philosophy of Systems Modeling

This is a general attitude or philosophy towards system modeling that says testing is required to verify system operation and subsystem performance (fuel element tests, separate effects test of physical parameters, and separate flow tests through components).

The Hubble telescope had significant problems because it wasn't tested before launch. Skylab was damaged during launch because data from other vehicles was ignored. This is not intended to pick on NASA, there are other industries that have similar tales to tell. These were picked because they are recent or more easily identified by NASA.

SUMMARY

- CHALLENGES OF PBR MODELING AND SYSTEM ANALYSIS
- COMPUTER CODES
- PHYSICAL CORRELATIONS
- RESULTS OF ANALYSIS FOR DECAY HEAT COOLING AND STARTUP
- PHILOSOPHY OF SYSTEMS MODELING

View Graph 32 - Summary

In summary this presentation has covered the characteristics and some challenges of Particle Bed Reactor modeling. It covered the major components of modeling; Computer codes, physical correlations used, a test philosophy, and selected results of decay heat cooling and start-up analyses.

Finally, there was an appeal to all of us to keep in mind the necessity of obtaining experimental data to verify systems performance and systems models.

FINAL THOUGHTS

- **NOBODY BELIEVES THE ANALYSIS EXCEPT THE ANALYST**
- **EVERYBODY BELIEVES THE EXPERIMENT EXCEPT THE EXPERIMENTALYST**
  - **Seen on NASA wall**
- **"PAPER REACTORS, REAL REACTORS" Admiral Hyman Rickover - 1953**

View Graph 33 - Final Thoughts

In parting, I'll leave you with these words which were seen on a NASA wall poster during a recent visit to the Huntsville Space Center. I have included in the written version of this presentation some excerpts from a paper entitled "Paper Reactors, Real Reactors" written by Admiral Hymen Rickover in 1953. As we all know, the Admiral ran a very successful, man-rated nuclear propulsion program. I won't take the time to read this to you here, but urge you to take a look at this excerpt and remember that times have not changed significantly in the 40 years since this was written. This excerpt can be summarized by saying that "paper reactors always run better than real reactors".

PAPER REACTORS, REAL REACTORS

Admiral Hyman Rickover, *The Journal of Reactor Science and Engineering,* June 1953

An academic reactor or reactor plant almost always has the following basic characteristics: *1) It is simple. 2) It is small. 3) It is cheap. 4) It is light. 5) It can be built very quickly. 6) It is very flexible in purpose. 7) Very little development is required. It will use mostly off-the-shelf components. 8) The reactor is in the study phase.* It is not being built now.

On the other hand, a practical reactor plant can be distinguished by the following characteristics: *1) It is being built now. 2) It is behind schedule. 3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. 4) It is very expensive. 5) It takes a long time to build because of the engineering development problems. 6) It is large. 7) It is heavy. 8) It is complicated.*

The tools of the academic reactor-designer are a piece of paper and a pencil with an eraser. If a mistake is made, it can always be erased and changed. If the practical-reactor designer errs, he wears the mistake around his neck; it cannot be erased. Everyone can see it.

The academic-reactor designer is a dilettante. He has not had to assume any real responsibility in connection with his projects. He is free to luxuriate in elegant ideas, the practical shortcomings of which can be relegated to the category of "mere technical details." The practical-reactor designer must live with these same technical details. Although recalcitrant and awkward, they must be solved and cannot be put off until tommorrow. Their solution requires manpower, time and money.

Unfortunately for those who must make far-reaching decisions without the benefit of an intimate knowledge of reactor technology, and unfortunately for the interested public, it is much easier to get the academic side of an issue than the practical side. For a large part those involved with the academic reactors have more inclination and time to present their ideas in reports and orally to those who will listen. Since they are innocently unaware of the real but hidden difficulties of their plans, they speak with great facility and confidence. Those involved with practical reactors, humbled by their experiences, speak less and worry more.

Yet it is incumbent on those in high places to make wise decisions and it is reasonable and important that the public be correctly informed. It is consequently incumbent on all of us to state the facts as forthrightly as possible.